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The Boundary/Pedestal Integrated Science Application for FSP

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I. Introduction

This Integrated Science Application (ISA) represents a combination of the former Integrated Boundary and Pedestal Science Drivers carried out over the last year as part of the Fusion Simulation Program's planning phase. Those Science Driver plans, as well as four others, can be viewed on the website (http://fspscidri.web.lehigh.edu/index.php/Main_Page). The Boundary Science Driver report is also available as LLNL document LLNL-TR-471260. The plans described in those documents assumed ample resources would be available. This document represents a plan of vital importance for developing powerful simulation tools for magnetic fusion energy devices, but is of substantially less scope than the original Science Drivers because of budget limitations and the fact that here two Science Drivers are merged owing to the close proximity of the two regions that they model: (1) the warm plasma region known as the scrape-off layer (SOL) where magnetic field lines directly contact material structures together with the associate plasma-wall interactions and (2) the adjacent hotter plasma region know as the pedestal, which is the beginning of the confining closed magnetic field line core.

II. Overview and motivation

A. Pedestal physics and simulation

High performance ("H Mode") operation in tokamaks is achieved via the spontaneous formation of a transport barrier (or "pedestal") in the outer few percent of the confined plasma. This edge transport barrier strongly improves global energy confinement, and also generally improves global stability, resulting in dramatically enhanced fusion performance and the potential for more cost effective fusion reactors. However, the free energy in the large pressure gradient and the resulting bootstrap current in the pedestal can drive instabilities called Edge Localized Modes (ELMs), which periodically deposit impulsive heat and particle loads on plasma facing surfaces, and may reduce component lifetimes in reactor scale devices. A predictive understanding of pedestal formation and structure, as well as the physics of ELMs, is essential for prediction and optimization of the fusion performance of ITER and future reactors.

The plasma pressure typically increases by 1-2 orders of magnitude from the bottom of the pedestal (very near the magnetic separatrix) to the top, and increases by less than an order of magnitude from the pedestal top to the magnetic axis. Hence, while the pedestal occupies a relatively narrow radial region, it contains far more pressure gradient scale lengths than the core plasma. The impact on global confinement is amplified via coupling to the core plasma where transport is fairly stiff, meaning that the core profiles are closely correlated to critical gradient scale lengths. As a result, the core pressure increases roughly linearly with the pedestal pressure (or "pedestal height"), and the fusion power output scales roughly as the square of the pedestal height, providing a powerful lever for performance optimization of fusion systems. While the performance benefits of H-mode operation are dramatic, there is a potential drawback. The large pressure gradients in the edge barrier lead to large localized currents, via the bootstrap effect, and the substantial free energy present in both the pressure and current gradients drives the ELMs While ELMs are largely benign in existing devices, and can aid in density and impurity control, in future higher power devices, highly impulsive ELM heat and particle loads to plasma facing surfaces, which may constrain material lifetimes.

The pedestal presents a daunting set of challenges to traditional theoretical and computational methods. Because the pressure varies by 1-2 orders of magnitude across the pedestal, and the density, temperature, flow velocity, radial electric field and current also vary substantially, a very wide range of key dimensionless parameters is encompassed in this region. For example, the pedestal plasma often transitions from being nearly collisionless near the top of the pedestal, to strongly collisional at the bottom, requiring methods appropriate for both regimes. More fundamentally, the broad range and overlap of spatiotemporal scales across the pedestal deeply challenges the assumed separation of equilibrium ("macro") and turbulence ("micro") scales upon which most existing theory and computation relies, and thus extensions of basic theory and massive computational resources are expected to be needed. For example, across a single pedestal, the timescales associated with electron drift waves span a wide range (due to the wide variation of equilibrium quantities) which overlaps with the wide range of temporal scales associated with Alfven waves, which in turn overlaps ion drift wave and ion transit temporal scales, which in turn can overlap the fast timescales on which the equilibrium itself is observed to evolve, for example during an ELM. The range of overlapping temporal scales often exceeds six orders of magnitude. A similar overlap is found in physically relevant spatial scales, where the gyroradius and ion drift wave scales can overlap the short gradient scale lengths.

Despite these challenges, there has been substantial recent progress in understanding key pedestal physics issues, and in developing computational tools suitable for pedestal studies. The onset of ("Type I") ELMs, and a crucial constraint on the pedestal height, has been found to be due to the onset of intermediate wavelength MHD modes, known as "peeling-ballooning modes" because they are driven by a combination of the pressure gradient (ballooning) and edge current (peeling or kink) drives. Efficient linear codes have been developed for calculating the peeling-ballooning mode onset condition. Nonlinear simulations using Braginskii fluid equations [Braginskii 65], extended MHD, and gyrofluid codes have explored ELM dynamics with increasing physical realism. Static models of the pedestal height and width have been developed by combining the peeling-ballooning constraint with another linear constraint, such as that for stiff onset of kinetic ballooning modes. These models, without any fit parameters, have proved to be reasonably accurate in predicting the pedestal height in the high performance H-mode regime on a number of devices, though a number of extensions can be considered. A set of computational tools have been developed to begin the study of dynamic evolution of the pedestal. Neoclassical transport codes, including fast steady-state solvers, and large-scale initial-value simulations have been developed to treat the pedestal region, and tested, identifying significant ion thermal transport and potential effects due to ion orbit losses. Closed field line gyrokinetic solvers initially developed for the core region inside the pedestal have been extended to include fully electromagnetic perturbations and more realistic collision operators, potentially enabling their use in pedestal studies, both linear and nonlinear. Gyrokinetic codes incorporating both the closed field line (pedestal) region, and the open field line SOL region are under development by a pair of US-DOE projects (CPES and ESL).

The practical goal for pedestal research is to achieve operation with a high pressure pedestal with a profile relaxation mechanism which does not present the material interface with unacceptable transient heat loads – that is to operate with small or no ELMs. For modeling, the goal is to develop the capabilities to understand and predict:

(A) the onset of edge barriers (or "L-H transition") as well as the transition from low to high performance H-mode,

(B) the structure of the barrier in all profiles (with particular initial emphasis on the pressure at the top of the pedestal), and

(C) the nature of the pedestal relaxation, particularly ELMs, and to identify and optimize methods for reducing transient heat deposition on material surfaces (including ELM-free and small ELM regimes, as well as suppressing or mitigating ELMs via external control techniques, including magnetic perturbations or pellets).

Successful achievement of these goals will require modeling that not only addresses the substantial challenges of the pedestal region itself, but which also couples closely to the open field line region, including the scrape-off-layer, divertor and material surfaces, as well as to the deeper core plasma.

B. Boundary/wall physics and simulation

Plasma, neutral gas, and wall processes in the scrape-off layer (SOL) region just outside the magnetic separatrix dividing closed and open magnetic fields line regions play a key role in determining the heat and particle fluxes to material surfaces, both from steady-state or between-ELM periods and from ELMs themselves. While the neutron flux to surrounding walls is broadly distributed, the exhaust plasma fluxes are typically very concentrated owing to anisotropic transport properties of the strong magnetic field even on open field lines. A central issue for future magnetic fusion devices is operating them such that the steady-state peak heat flux to materials does not exceed ~10 MW/m^2, which is believed challenging for ITER and an unsolved problem for higher power future devices. For transient heat loads such as ELMs there is a fundamental material melting or vaporization limit of $\Delta S_p \tau_L^{-1/2}$ ~40 MJ m^{-2} s$^{-1/2}$, where ΔS_p is the energy released by the ELM divided by the area affected on the divertor surface, and τ_L is the time for the energy to be lost to the material surface. Among additional major issues are removal of helium ash and tritium, impurity production and transport to the core region, material lifetime, and impact of intense events that periodically eject large energies into the SOL over a short time. Considerably greater detail on these processes and issue associated with them is given in the original Science Driver report mentioned in the introduction.

The general focus of the boundary task area is to produce an integrated model of that region that accounts for plasma collisional and turbulent transport, neutral/plasma interactions, and wall interactions, much as discussed in the original Science Driver. However, owing to the reduced scope of the present ISA, a number of the components will need to come from simplified existing models. In particular, neutral models and plasma wall interactions will rely largely on present models, while the coupling of plasma collisional and fundamental turbulent transport will be more completely developed as a fully functional coupled transport/turbulence SOL model does not exist.

The initial focus is on fluid models because of their lower dimensionality compared to kinetic models and because some present-day devices operate in strongly collisional regime. This SOL simulation model must be able to simulate long timescales, ~10^{-1} secs for present-day devices using a fixed-temperature wall model owing to wall recycling. The timescale will be much longer when the wall temperature is allowed to evolve. Some resources will be expended to provide coupling between the plasma model and neutrals plus wall interactions (recycling and sputtering) and some cross-cutting resources will be used to improve the implicitness of the numerical algorithms for these models. It is hoped that improvements can be made to plasma/wall interaction physics models through new funding sources such as a possible SciDAC project in FY12.

Three reasons for this prioritization are that (1) SOL turbulence and resulting transport across the magnetic field is believed to strongly effect the peak heat flux to divertor surfaces, a major issue for successful operation of ITER and other devices, (2) the readiness of 3D fluid turbulence codes to simulate the turbulence with intermittent plasma “blob” transport observed in the SOL, and (3) an initial focus on plasma turbulence and transport that includes neutrals is of great relevance to the pedestal region and should provide a direct avenue for coupling or integrating the two regions in this ISA. In addition, both the SOL and pedestal regions have important kinetic plasma effects that can span long to short Coulomb mean-free paths and thus require an accurate Fokker-Planck operator. Furthermore, the generation of blobs that transport plasma into the SOL likely takes place near the magnetic separatrix, so a portion of the pedestal region should be included for SOL simulations.

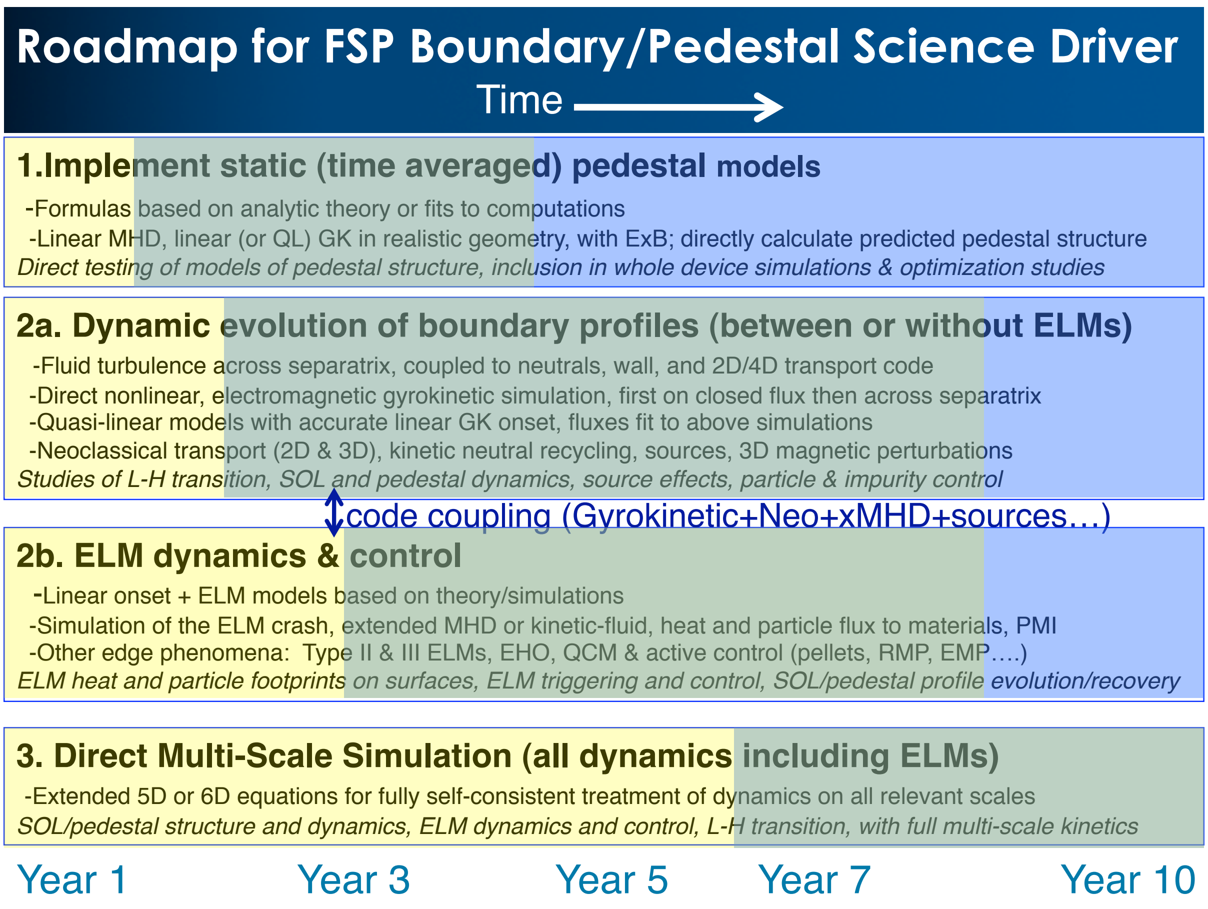

Figure 1: The three level roadmap for the combined boundary/pedestal ISA, indicating sets of major tasks (1, 2a&b, 3) that are planned. Each level of the roadmap (1,2 &3) will begin with a development, implementaion and verification stage (shaded yellow), followed by a validation and ongoing development stage (shaded green), and finally a stage of routine application, with minor ongoing development (shaded blue). The major emphasis in the reduced scope plan will be on Level 2, particularly 2a, for both the boundary and pedestal regions.

III. Roadmap for the Development of Boundary/Pedestal Simulations

The goals, challenges and progress described above lend themselves to a three-level plan for the FSP boundary/pedestal ISA effort. This plan, illustrated in Fig. 1, addresses both the need to deliver world-leading capability on a relatively short timescale, and the need to address the deeper fundamental challenges associated with pedestal/SOL/wall dynamics, taking advantage of peta- and exa- scale computing capability as it becomes available.

There are a number of computational approaches that can be applied with increasing physics fidelity but also with increasing challenge to theory and computation. At the first level, the physics of the static (i.e., time-averaged) pedestal can be addressed via linear physics models, based on existing models and their extensions. At the 2^{nd} level, dynamics of the boundary and pedestal are considered, but a separation is initially maintained between the physics models for the ELM event itself, and the dynamics between, or in the absence of, ELMs. The full dynamics of the SOL/wall will be the initial focus for the boundary area. A wide variety of available and developing tools can be used to treat neoclassical and turbulent transport between ELMs, including 3D fluid and gyrofluid codes and 5D electromagnetic gyrokinetic simulation codes. Full f codes can potentially be used to treat larger perturbations, but will require further development. At this level, the ELM event itself will be treated separately, via calculations of its onset and dynamics with extended MHD or gyrofluid codes. Finally, at Level 3, dynamics across all relevant scales, including ELMs, will be treated self-consistently with a single simulation code. Additional advancements in theoretical gyrokinetic algorithms, and possibly formulations, to allow fully electromagnetic simulations of arbitrary scale electromagnetic modes in cross-separatrix geometry may be required. The most complete models would be 6D full kinetic simulations using the full collision operator. The computational challenge that this would present suggests that its use, at least initially, would be for assessment of the less complete models, though in the longer term, with sufficient computational power becomes available, more extensive use could become practical.

This general outline leads to a corresponding development roadmap with three levels and four major elements, illustrated with a timeline in Figure 1. Note that due to reduced resources, several aspects of the plan will have to rely heavily on theory and code development efforts outside of FSP. In particular, Level 1 will consist largely of implementation of existing codes and models for the pedestal, Level 2 will be the primary area of focus for this ISA, and work in Level 3 will be largely at an exploratory level of effort. As discussed more fully below, the 2-year milestone for the pedestal region lies in Level 1, whereas for the boundary area, the 2-year goal is in Level 2.

Level 1. Linear models for pedestal structure

This step would begin with componentization of existing models that solve for static (time averaged) pedestal structure via linear stability analysis, for example, that of peeling-ballooning and kinetic ballooning modes. Improvements can come through use of linear or quasi-linear gyrokinetic calculations, more realistic geometry and inclusion of ExB stabilization. This analysis typically requires hundreds or thousands of independent MHD and/or gyrokinetic stability calculations with trial equilibria. Key issues are robustness, error checking, automation, and, particularly in the case of gyrokinetic calculations, efficiency. Extensive comparison with experimental data sets will be carried out. It is expected that this capability can be made available relatively quickly, allowing a world-leading capability for coupled pedestal-core optimization of fusion systems. (Task A)

Level 2. Dynamic evolution of the boundary and pedestal via separate inter-ELM and ELM components

2a. Dynamic evolution of boundary and pedestal profiles between ELMs

In the near term, dynamics in the boundary region are expected to be addressed with 3D fluid simulations codes coupled to 2D transport codes, and models for neutral and materials physics (Task B). In the medium term, kinetic plasma and neutral transport effects are added (Tasks C and D). In the longer term, the fundamental tool for calculating boundary and pedestal transport between ELMs is expected to be electromagnetic gyrokinetic simulations of turbulent transport including a realistic collision operator and to separate calculations of neoclassical transport, sources and material interaction (Task E). It is envisioned that nonlinear simulations will be employed both for development of simplified transport models, as well as for direct calculations of particle, momentum and heat transport (Task E). Neoclassical calculations will eventually include 3D equilibrium effects, such as neoclassical toroidal viscosity. A plasma-material interaction (PMI) models will be coupled to the SOL plasma/neutral description. All of these models would need to be appropriately verified, including extensive verification of reduced dynamic models against direct nonlinear simulations, and validated against experimental measurements.

2b. ELM dynamics & control with fluid or kinetic-fluid hybrid models

The models described above would be extended by simulation of phenomena that limit or control the pedestal/SOL pressure gradients. These would include spontaneous plasma behavior [ELMs of various types, Edge Harmonic Oscillation (EHO), Quasi-Coherent Mode (QCM), etc.] and active control through pellets, resonant magnetic perturbations (RMP), electromagnetic perturbations, etc. The work could begin with linear onset from peeling-ballooning calculations, coupled to simple ELM crash models. The next step would be direct simulation of ELM dynamics using extended MHD or two-fluid and/or kinetic-fluid codes for the plasma (Task E). These codes would need to include realistic calculations of parallel transport and transient heat and particle loads onto material surfaces, where again a PMI model will provide the response back on the plasma/neutral solution. Validation experiments could compare ELM (or other mode) structure, dynamic modification of pedestal/SOL profiles, heat and particle footprints and ELM control mechanisms.

Level 3: Direct Multi-Scale Simulation

The prior computational stages use gyrokinetic calculations for modeling the micro-scale and extended MHD for the macro-scale. However, as noted above, these overlap strongly in the edge barrier. Some systematic study will be required to test the assumption of spatiotemporal scale separation, to determine when and how it breaks down and to assess the consequences. Numerical and theoretical progress will be required to develop and implement verified formulations and codes that can simulate multi-scale electromagnetic modes and turbulence in separatrix geometry. Several approaches are possible including gyrokinetic treatments without the high-n approximation, kinetic-fluid methods and 6D Vlasov treatments including the full collision operator (Task F). The last of these plasma model issues, in particular, will require substantial progress in numerics to be practical. There is likewise a hierarchy of multi-scale PMI models including fundamental sputtering codes, kinetic Monte Carlo for surface interactions, and surface evolution that will be used to verify higher-level models that are more flexible for coupling in whole-region and whole-device codes. These plasma, neutral, and wall models would support the most fundamental studies of boundary and pedestal physics including L-H threshold, coupling of turbulence and equilibrium scales, ELMs and ELM control, heat flux to materials, and their evolution.

IV. Tasks and Milestones

Tasks for Years 1-2 *(see Table 2 for effort levels)*

A. Static (Linear) Models for Pedestal structure (2-year milestone)

This task will consist primarily of the implementation and testing of existing models of the pedestal structure, based on theory and linear MHD and gyrokinetic calculations

i. Componentization and verification of existing linear MHD and gyrokinetic codes

ii. Validation and development of extensions to models

B. Coupled fluid turbulence/transport/wall models (2-year milestone)

The largest gap that will be addressed in this 2-year period is coupling SOL turbulence to long-time plasma/neutral transport using fluid models. In addition, there will be coupling to a wall model, and a near-sheath plasma model. Examples of simulation codes exist for all of the individual processes and some also integrate multiple processes, but a routine coupled transport/turbulence model does not exist. In addition, a smaller amount of work will begin on kinetic models in this period, but full implementation of those will be directed at the 5-year milestone.

i. The turbulence in a small region about the separatrix and into the SOL is typically more intermittent and larger amplitude than in the core region. Thus, two strategies will be considered to profile long-time coupling between plasma transport and turbulence. The first is to embed a dynamic fluid neutral model including material recycling within a 3D turbulence code for observed drift-type modes, thus allowing the turbulence code to evolve its own axisymmetric plasma profiles. The second approach is to couple the 3D turbulence code with a 2D transport code (plasma and neutrals) using, for example, the relaxed iteration coupling (RIC) algorithm [Shestakov 03]; some preliminary development has already been done for application of this method to SOL turbulence and transport [Rognlien 05]. These two approaches will be evaluated in the first six months, followed by a focused effort on the most promising. Central questions to be resolve are practicality of very long simulations runs while maintaining particle and energy conservation and the applicability of the RIC method to moderately strong, intermittent transport events.

ii. Simplified models of plasma recycling at material surfaces are present in existing plasma transport codes. However dynamic wall processes, such as hydrogen accumulation in new conditioned walls (a standard procedure in many tokamak before each discharge) and ejection of hydrogen (out-gassing) in response to wall temperature increases, are not taken into account in a self-consistent manner. Wall codes have now been developed that can describe these time-dependent processes [Hassanein 02, Pigarov 09]. The task here is to couple an existing model to both transport and turbulent plasma/neutral models, but not to further develop the models unless incremental funds are available. Some initial work has been done in the FACETS SciDAC in this direction that can likely be utilized. Important developments that will be needed are to make the coupling implicit in time as well as the wall code itself to allow appropriate long-time simulations.

C. Preparation of kinetic models (toward 5-year milestone)

iii. As particles are recycling or sputtered from material surfaces, they penetrate some distance into the plasma before being ionized. It the ionization rate is sufficiently large, the ionization takes place very close to the material and their ion gyro-radii may allow prompt re-deposition to the wall [Brooks 02]. Such a process gives a net sputtering of impurities and is important in determining the evolution of the surface material, especially as it relates to sputtering impurities and separate deuterium and tritium transport during the many particle recycling/re-deposition events. The task is to develop an implicit solver for the shear model and begin work on implicit coupling strategies that minimize the impact of particle noise.

iv. Coupling fluid and kinetic neutrals is important, especially in the low-density periphery of the SOL. Here the issue of particle noise on the coupling needs to be addressed if the kinetic model is particle-based Monte Carlo [Stotler 01]. While development of a hybrid fluid/kinetic neutral model would be very useful, this task is not explicitly part of the reduce-effort work proposed here; instead we plan a progression for a flux-limited fluid model to a kinetic model for neutrals.

v. Prompt drift-orbit loss of energetic ions near the separatrix may produce an important heat-flux component to the divertor plate [Chang 04]. Consequently, it is important to eventually include a kinetic ion transport model in the SOL. Likewise, parallel electron transport in the SOL can have energetic tail electrons owing to parallel kinetic effects [Batishchev 97]. Both of these ion and electron kinetic effects will require an accurate Coulomb collision operator, and cross-cutting work will begin on the task of finding a method for efficient calculation of Rosenbluth potentials.

Tasks for Years 3-5 *(see Table 2 for effort levels)*

The first 5-year boundary milestone is to generalize the basic fluid 2-year model to include kinetic effects for transport across the magnetic field as well as along it. The initial turbulence code that provides the turbulent fluxes will still be an electromagnetic fluid model. Work will be done to develop an electromagnetic kinetic SOL turbulence code, but at the constrained budget level, its completion in the 5-year timeframe is not proposed.

The second 5-year milestone involves dynamic modeling of the pedestal, based on nonlinear, dynamic kinetic descriptions, initially on closed field lines, and then extending across the separatrix and combining with the SOL/divertor/wall simulation efforts.

D. *Coupled kinetic-transport/fluid-turbulence; improved wall/sheath models (5-year milestone)*

i. A 4D (2r,2v) axisymmetric kinetic transport model for ions and electrons will be coupled to a 3D turbulence model, likely initially fluid-based, for long-time transport simulations. As with the fluid model, particle recycling produces a long time-scale of ~0.1 s that must be accommodated; the kinetic transport model will thus need to use an implicit time-advance method. The kinetic collision operator will include charge-exchange and a source term for ionization/recombination.

ii. A kinetic neutral model will be coupled to the plasma model or a sufficiently parameterized, verified reduced fluid model will be used. Implicit coupling will be developed.

iii. As for the 2-year milestone, a dynamic wall model will be coupled to the plasma/neutral system. Here the generalization to non-Maxwellian particle and energy fluxes will be included in the wall model.

iv. Impurities will be included in the fluid transport and turbulence models. These in turn will be couple to a near-sheath impurity model for re-deposition of sputtered material. This work will set the stage for adding impurities in the kinetic plasma/neutrals models beyond the 5-year timeframe.

E. *Dynamic evolution of pedestal profiles (5-year milestone)*

Existing substantial efforts in edge and core gyrokinetics and extended MHD provide a good starting point. Thus, initial efforts will involve adapting existing components to requirements for the FSP. This is a large, broad task and substantial resources will be required. Bulk of effort will initially be towards development, with emphasis switching to new science and V&V in out years

i. Componentization and verification of existing nonlinear MHD and electromagnetic gyrokinetic codes

ii. Coupling of initial MHD and/or fluid ELM ejection model to SOL/wall model

iii. Design and development of new capabilities (e.g., free boundary equilibrium solver accurate to SOL; ion-electron GK with magnetic perturbations, etc.)

iv. Experimental validation and new science investigations

F. *Coupled gyrokinetic pedestal/SOL/wall (8-year milestone)*

Owing to their close proximity and strong interaction, a unified kinetic model of the pedestal and SOL will be developed. The description of electromagnetic turbulence will be especially challenging owing to large-amplitude perturbations in the SOL, as well as efficient coupling to kinetic neutrals and the wall.

i. Complete 5D (3r,2v) electromagnetic turbulence code capable of microturbulence across the pedestal and SOL

ii. Couple kinetic turbulence to kinetic plasma and neutral transport and wall response for long-time simulations

iii. Include PMI with material surface evolution

G. Direct multi-scale simulations (12-year milestone)

Owing to the lack of strong scale separation between equilibrium and fluctuating quantities in the pedestal/boundary regions, it is important to assess the accuracy of the gyrokinetic models based on expansion techniques (see Level 3 description above).

i. Generalized gyrokinetic analysis

ii. Assess kinetic-fluid hybrid and 6D ion kinetic models

iii. Provide integration of multi-scale PMI processes

Table 1: Application and Supporting Technology Tasks and Resources

Milestone (time)	Application work	Supporting work
A) Static Pedestal: Linear MHD/kinetic-microturbulence stability boundaries (2 year)	Perform multi-parameter stability studies with gyro-kinetic/ MHD/ fluid codes	Kinetic collision operator
B) Fluid SOL/wall: Coupled plasma transport/ turbulence/ gas/ wall (2 year)	Establish 2-way couplings btwn components; then couple all components	Implicit solver for fluid turbulence & wall; implicit coupling; framework?
D) Kinetic SOL/wall: Coupled SOL kinetic transport/plasma turbulence/gas/wall (5 year)	Add kinetic transport models for plasma/ gas/; enhanced wall model	Implicit solver for kinetic transport code; implicit kinetic coupling; particle noise; Coulomb collision operator; framework
E) Dynamic Pedestal: Nonlinear MHD/kinetic microturbulence transport (5 year)	Pedestal profile evolution with kinetic code; add neutrals/ begin ELM loss	
(long term) Coupled kinetic pedestal/SOL/wall: Nonlinear evolution of pedestal/ SOL/ wall with self-consistent turbulence, and some multi-scale capability (8-10 year)	Couple kinetic pedestal and SOL/wall components; consistent ELM coupling; kinetic SOL turbulence	Implicit kinetic coupling; particle noise; Coulomb collision operator; framework

Table 2: Resources in FTE for Boundary/Pedestal tasks. This table gives the resources allocated within the ISA group itself for the first five years of the project. A similar level of supporting resources across the organization are expected for successful task completion.

<table>
<tr><th>Year/Task</th><th>Yr 1</th><th>Yr 2</th><th>Yr 3</th><th>Yr 4</th><th>Yr 5</th></tr>
<tr><td>Static Pedestal Model</td><td>1.5</td><td>1.5</td><td>1</td><td>0.5</td><td>0.5</td></tr>
<tr><td>Long-scale fluid turb. with transp</td><td>2</td><td rowspan="2">3</td><td></td><td></td><td></td></tr>
<tr><td>Iterative fluid turb/transp.</td><td>1</td><td></td><td></td><td></td></tr>
<tr><td>Add impurit. to SOL turb.</td><td></td><td></td><td>0.5</td><td>0.25</td><td></td></tr>
<tr><td>Couple wall uptake/ release/ temp</td><td>0.5</td><td>0.5</td><td>0.5</td><td>0.5</td><td>0.25</td></tr>
<tr><td>Kinetic sheath model</td><td>0.25</td><td>0.25</td><td>0.5</td><td>0.5</td><td>0.25</td></tr>
<tr><td>Couple fluid/ kinetic neutr.</td><td>0.5</td><td>0.5</td><td>0.5</td><td>0.75</td><td>0.5</td></tr>
<tr><td>Kinetic collis. with CX, ioniz</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.5</td><td>0.5</td></tr>
<tr><td>Couple fluid turb / kinetic transp</td><td></td><td></td><td>0.75</td><td>1</td><td>1</td></tr>
<tr><td>ELM simulation</td><td>0.5</td><td>0.5</td><td>0.5</td><td>0.5</td><td>0.5</td></tr>
<tr><td>Kinetic turbulence</td><td>0.5</td><td>1.5</td><td>2.5</td><td>2.5</td><td>2.5</td></tr>
<tr><td>kinetic turb/ kinetic transp incl. neoclassical</td><td></td><td>1</td><td>1.5</td><td>1.5</td><td>1.5</td></tr>
<tr><td>Validation</td><td></td><td>1</td><td>2</td><td>2</td><td>2</td></tr>
<tr><td>TOTAL</td><td>7</td><td>10</td><td>10.5</td><td>10.5</td><td>9.5</td></tr>
</table>

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